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No. 718

RESISTANCE OF TRANSPARENT PLASTICS TO IMPACT

By Benjamin M. Axilrod and Gordon M. Kline
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I. INTRODUCTION

The problem of developing a windshield for aircraft which will withstand the effect of bird impacts during flight is a difficult one, as an estimate of the striking energy will indicate. If the average speed of the airplane is considered to be about 200 miles per hour and that of the bird about 70 miles per hour, the speed of the bird relative to the airplane may be as great as 400 feet per second. If a 4-pound bird is involved, a maximum impact energy of approximately 10,000 foot-pounds must be dissipated. To obtain this energy in a drop test in the Washington Monument, it would be necessary to drop a 20-pound weight down the 500-foot shaft. For both theoretical and practical reasons, it is necessary to keep the mass and speed more nearly like those to be encountered. However, to get an impact of about 10,000 foot-pounds with a 4-pound falling body, it would be necessary to drop it from a height of approximately one-half mile, neglecting air resistance. These facts will indicate some of the experimental obstacles in the way of simulating bird impacts against aircraft windshields.

This report presents the results of a comparative study of the impact strengths of various types of transparent plastics with particular reference to their ability to withstand the impacts of relatively soft bodies.

II. TEST MATERIALS AND METHODS

The following types of plastics were tested: Cellulose acetate, cellulose acetopropionate, cellulose nitrate, ethyl-cellulose, vinyl chloride-acetate, vinyl acetal, methyl methacrylate, propyl methacrylate, and butyl methacrylate. Of these plastics, only cellulose acetate, cellulose nitrate, and methyl methacrylate are or have been used in aircraft windshields; the other materials were submitted as experimental products. Each sample has been assigned a symbol comprised of a letter and a number. The letter is used in place of the name of the manufacturer and the numbers indicate different nominal thicknesses or different formulas of a given manufacturer's plastic.

Three different methods of testing the plastics for impact strength were used, namely, the Charpy pendulum type of impact testing apparatus, drop tests with hard and relatively soft bodies, and high velocity impacts produced by projecting a body from a gun by air or powder.

III. CHARPY IMPACT TESTS ON PLASTICS

A. Apparatus and Significance of the Tests

The apparatus used in the measurement of Charpy impact strength is shown in figure 1. The capacity of the machine is 2.9 foot-pounds and its striking velocity is about 8 feet per second. The specimen was prepared in the form of a bar 2.5 inches long, 0.5 inch wide, and thickness as received. The material was tested with a notch cut into the edge of the specimen, as shown in figure 2. The specimen

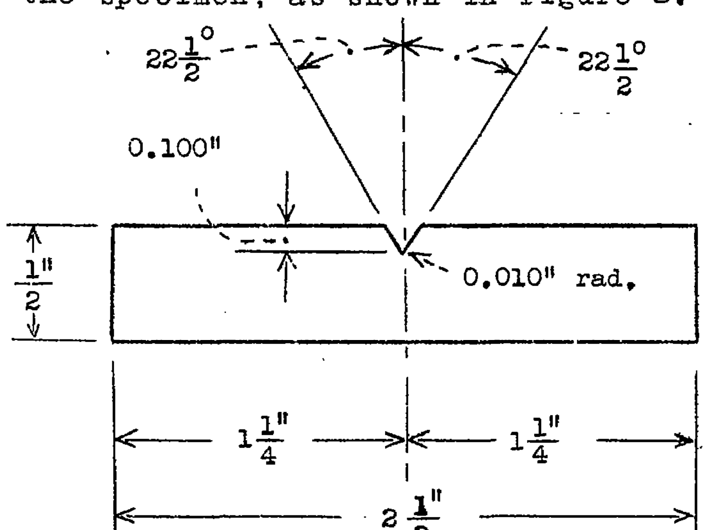

Figure 2.- Specimen for Charpy impact strength test (thickness of specimen is same as that of the sheet to be tested).

was broken as a simple beam, the blow being struck by the rounded knife edge of the pendulum at the middle of the span, which was 1.57 inches. The specimens were struck on the edge opposite the notch. The scale was graduated in degrees and readings were estimated to 0.1°, which corresponds approximately to 0.002 foot-pound.*

The pendulum test is quite arbitrary in that the type of impact to which a material may be subjected in actual use may be very different from that in the Charpy test, especially with regard to the concentration of the load. It is possible that in service a large portion of the material is stressed highly, whereas in the pendulum test, only the material near the midspan is subjected to high stresses. The latter is particularly true for the notched specimens. At the base of the notch there exists a very high stress concentration which depends on the radius of curvature. Notching the specimen makes it possible to break ductile or flexible materials which otherwise would bend and pass between the supports without fracture. The unnotched specimen gives a higher strength value than the notched specimen, and the ratio of the strength of the unnotched specimen to that of the notched specimens varies with different materials. Inasmuch as the unnotched cellulose plastic specimens, in general, tended to pull through with the pendulum at room temperature without breaking, all of the Charpy tests described in this report were made with notched specimens.

B. Results of Charpy Impact Tests

For one series of Charpy impact tests, two sets of five notched specimens of each material were prepared. The edges were machined on a milling machine and the notch was made with a 60° triangular file. One set was tested at 70° F. and 65 percent relative humidity, and the other at about 25° F. without humidity control. The results of these tests are presented in table I. As the materials tested were of different thicknesses, the data are reported in foot-pounds per inch of thickness, obtained by dividing the observed value for the energy absorbed in breaking the specimen by its thickness.**

In the course of experimental work with samples of transparent plastics submitted subsequent to the above tests, additional data on impact strength as measured by the Charpy test were obtained. The specimens for these tests were notched with a special milling cutter designed

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*For further details of the Charpy impact strength test, see A.S.T.M. Tentative Standards, 1937, page 1023.

**See A.S.T.M. Tentative Standards, 1937, page 1028.

to produce the type of notch indicated in figure 2. Four to six specimens of each sample were tested. The averaged results of these miscellaneous tests are shown in table II. In particular, the effect of fastening a bracket to each support slightly above the specimen to eliminate the possibility of the thin specimens flipping over and breaking in a flatwise instead of an edgewise position, was determined. No significant difference in the results obtained was noted. The decreased impact strength of cellulose acetate and cellulose acetopropionate at low temperatures and the negligible effect of temperature on methyl, propyl, and butyl methacrylate, and styrene resins are also shown in these tests.

IV. FALLING-BODY IMPACT TESTS ON PLASTICS

A. Falling-Ball Tests

A falling-ball test for laminated glass described in a publication of the American Standards Association* provides for dropping a 0.5-pound steel ball 10 feet onto the center of a 12-inch square specimen resting in a wooden frame (fig. 3), which has an opening 11-3/8 inches square. Following this specification except for the height, it was found that a cellulose-acetate specimen, 94 mils thick, failed only on the 24th impact of the 0.5-pound steel ball falling 65 feet. A cellulose-nitrate specimen, 65 mils thick, was forced into the hollow center of the supporting rack without fracturing on the first impact from 65 feet. In order to avoid this action and to reduce the time required for the test, the following test procedure was adopted. A specimen 6.5 inches in diameter is fastened firmly between rubber gaskets in a metal frame (fig. 4) which has a circular opening 5.5 inches in diameter. The least height from which the test body falling onto the center of the plastic will break it with two impacts is determined, except for those plastics which do not break on the second impact from 65 feet, the maximum height which was available for this test. For these latter materials, the total number of impacts from 65 feet required to break the specimen, is determined.

Some results of the falling-ball tests are given in table I. (See also specimens 1 and 2 in fig. 5.) The impact strengths, as measured by the ball impact method, may be compared with the Charpy impact values for various

*"Safety Code for Safety Glass for Glazing Motor Vehicles Operating on Land Highways," Z26.1-1935, American Standards Association.

plastics in table I. Fair correlation of results by the two methods is noted when specimens of approximately the same thickness are compared. Thus, the three samples of cellulose acetate approximately 1/16 inch thick have Charpy impact strengths averaging 2.8 foot-pounds per inch of thickness and require about two impacts with the 0.5-pound steel ball from 65 feet to cause fracture; the corresponding values for 1/16-inch-thick cellulose nitrate are 4.1 foot-pounds per inch of thickness and four impacts with the steel ball. The materials with low Charpy values, such as the methyl methacrylate and vinyl chloride-acetate resins are also readily broken by the 0.5-pound steel ball falling short distances.

In order to determine the effect of impacts of comparatively soft bodies on the plastics as compared with the impact of the steel ball, a tennis ball partially filled with lead shot was used in a series of tests reported in table III. (See also specimen 3 in fig. 5.) Results of tests on a few cellulose-acetate samples indicate that a given sample will withstand three times as many impacts from a 1-pound shot-filled tennis ball as from a 0.5-pound steel ball. A still less elastic ball was prepared by incorporating lead shot into a small amount of acoustic cement of doughlike consistency and molding this in the center of a hollow sponge rubber ball of 5-inch diameter and approximately 1-inch wall thickness. It will be noted in table III that a 13- by 17-inch cellulose-acetate sample, 0.138 inch thick, required seven impacts from 65 feet with this 4-pound sponge-rubber ball to cause failure.

The relative resistance to ball impacts of single, laminated, and composite cellulose-acetate materials, was determined with a 1.2-pound steel ball dropped from a height of 65 feet, on circular specimens fastened in the frame (fig. 4) having an opening 5-1/2 inches in diameter. The values obtained are shown in table IV. The laminated sheet was made up of three layers of the usual grade of cellulose-acetate sheet used for airplane windshields cemented together with two interlayers of soft cellulose-acetate plastic of the type employed in making laminated glass. The composite specimens consisted of the windshield grade of cellulose-acetate sheet clamped together without cementing material in the circular frame. The thick single specimens indicated in table IV as pressed from thinner sheets were prepared by the application of sufficient heat and pressure to cause the layers to flow and bond together. In general, the composite specimens had the greatest resistance to the impact of the 1.2-pound ball. For example, in thicknesses of approximately 0.25 inch, a composite specimen required 13 blows, a laminated specimen an average of 6 blows, and a single, pressed specimen an average of 3.5 blows. The values shown in table IV for cellulose-acetate sample C6 struck by a 1.2-pound steel ball, when compared with the value obtained with a heavier softer body (1.4-lb. shot-filled tennis ball) as presented in table III, serve to emphasize further the marked dependence of impact resistance of plastics on the relative deformability of the striking object.

B. Falling-Dart Tests on Plastics

In the course of some experiments with laminated and tempered glass, conducted by the Glass Section of the National Bureau of Standards, a dart weighing approximately 3-3/4 pounds was utilized as the striking body. (See fig. 6.) It consisted of a cylindrical piece of steel fitted with a solid sponge-rubber ball in the striking end and a wooden stick 2 feet long in the other end. A piece of steel was inserted in the end of the stick to hold the dart against the same magnetic release used in dropping the steel balls. This same dart was also employed in testing samples of methyl-methacrylate and cellulose-acetate plastics, particularly with respect to their comparative resistance to impact at 100° and 0° F. The plastics were tested in the form of 12- by 12-inch sheets laid in the frame ordinarily employed in testing laminated glass (fig. 3) except that the tests on cellulose-acetate sheets at 100° F. had to be made with the samples clamped in the square frame shown in figure 7, because the sheets pulled through the former frame without breaking. The samples were removed from the oven or refrigerator, and subjected to the impact of the dart within approximately 30 seconds.

The results of the falling-dart tests on various thicknesses of methyl-methacrylate resin and on 1/8-inch-thick cellulose acetate are shown in table V. The resistance of the methyl-methacrylate resin to the impact of the dart was very surprising in view of the ready fracture of this plastic by the 0.5-pound steel ball. The comparative types of breaks obtained with the cellulose-acetate and methyl-methacrylate sheets at 0° F., are shown in figure 8.

V. HIGH VELOCITY IMPACT TESTS ON PLASTICS AND GLASS WINDSHIELD PRODUCTS

The experiments on the resistance of the plastics and laminated glass to impacts with bodies projected at high velocity from a gun, may be subdivided into three groups, namely, (1) tests made with an air gun, (2) tests made with an antiaircraft gun using black powder as the propellant, and (3) tests made with bullets fired from pistols and machine guns.

A. Impact Tests Made with an Air Gun

Various types of projectiles weighing approximately 1/2 pound were constructed and fired by means of 100 pounds air pressure from a 2-inch-bore air gun, shown in figure 9, with ballistic pendulum in place to determine the velocity of the projectile. For impact tests the pendulum was removed and the frame holding the sample was fastened in approximately the same position in such manner that the center portion of the specimen would be struck. The plastics were bolted into the frame (fig. 4) with an opening 5.5 inches in diameter, employed in making the falling-ball impact tests; the glass windshield products were placed in the wooden frame (fig. 3) with an opening 11-3/8 inches square, used in making the drop tests on these materials. The rubber projectiles used were of two types, one a vulcanized cylindrical projectile, approximately 2 inches in diameter and 4 inches long, wrapped in cellophane to reduce friction in passing through the gun barrel, and the other a soft unvulcanized rubber projectile prepared by rendering the rubber plastic by milling at an elevated temperature and incorporating Plastogen and forcing the plastic rubber into a cardboard sleeve approximately 2 inches in diameter and 5 inches long. This latter projectile deformed on striking the samples to a much greater extent than the vulcanized rubber product, the mark left on the target being about 3.5 inches in diameter. The data obtained in impact tests of these projectiles against various windshield materials are reported in table VI.

The circular samples of cellulose nitrate, approximately 65 mils thick, failed on the fourth impact with the vulcanized rubber projectile; the cellulose-acetate samples of similar thickness failed after 8 impacts in one test and resisted 12 impacts in another test. By the use of a cardboard sleeve in place of a wrapping of cellophane, higher velocity of the projectile, and hence increased energy in the impact, was obtained. Cellulose acetate of 65-mil thickness failed on three, four, and five impacts with this type of projectile. The same material in 125-mil thickness withstood 11 impacts with this soft-rubber projectile. The effect of the relative hardness of the projectile on the severity of the test, is indicated by the experiment in which three sheets of the cellulose nitrate of approximately 65-mil thickness clamped together in the circular frame were penetrated by one impact of a hardwood projectile (see specimen 4 in fig. 5), notwithstanding the fact that the energy involved was less than in the case of the soft-rubber projectile. The laminated and plate-glass samples tested in the frame shown in figure 3, failed on one impact of the soft-rubber projectile, whereas the tempered glass withstood six impacts, after which the test was discontinued.

B. Impact Tests Made with an Antiaircraft Gun

The resistance of various plastic and glass windshield products to high velocity impact was determined by firing a rubber-lead projectile from an antiaircraft gun of 5-inch bore. The projectiles were made by molding 1 pound of sponge rubber around a core consisting of a small rubber ball filled with sufficient lead shot to make the total weight 3, or 4 pounds, as desired. The sponge-rubber coating was approximately 1 inch thick and 45 percent voids. The projectiles were fired with from 100 to 200 grams of black powder, depending on the velocity desired. The velocity was determined by firing through copper-wire screens which were connected to a chronograph circuit. The target was approximately 50 feet from the muzzle of the gun. The windshield products tested were of two sizes, 14- by 18-inch and 12- by 12-inch, the thickness varying as indicated in the tables of results. The 14- by 18-inch specimens were fastened in the frame shown in figure 10, which has an opening 13 by 17 inches; the 12- by 12-inch specimens were clamped in one of similar construction having an opening 11 inches square (fig. 7). Soft sheet-rubber gaskets were inserted between the samples and metal. The windshield materials were tested with their surfaces normal to the path of the projectile and also at a 45° angle to its path.

The results of the tests* are presented in tables VII and VIII. It will be noted that in only two tests were the projectiles stopped by the samples, namely, by the four sheets of cellulose-acetate plastic of 0.516-inch total thickness and by the 1.25-inch heat-treated glass. In both cases the materials were struck by the projectile at an angle of 45° to its path. The projectiles weighed only 3 pounds, which is 1 pound less than the weight of the bird which was initially considered as representative of those to be encountered in flight. Likewise, the velocities were considerably less than the 400 feet per second originally specified for the test. In the remainder of the tests with the 3- and 4-pound projectiles at a 45° angle of impact, and in all of the tests at a 90° angle of impact, the projectiles penetrated the windshield products.

It is believed that a 4-pound projectile of the type employed, represents a more severe impact condition than would be involved in a collision with a bird of the same weight. The marked effect of the plastic nature of the colliding body on the ease of penetration of the windshield products, has been previously demonstrated in the tests with the falling objects and the air gun. However, it was not practical to fire a more plastic projectile from the antiaircraft gun because of the erratic flight which was obtained with softer projectiles due to their deformation while still in the barrel of the gun. These experiments with the antiaircraft gun, therefore, only indicate in a general way, the maximum requirements for a windshield which will withstand bird impacts. For the present, at least, the determination of the most suitable type of windshield can probably best be accomplished by drop tests on laminated glass and plastic products of the maximum weight that can be tolerated by aircraft manufacturers. The necessity for considering temperature cannot be overlooked because some plastics are a great deal weaker in impact strength at low temperatures than at ordinary temperatures.

C. Impact Tests Made with Bullets

Pistol bullets of various sizes and muzzle velocities were fired at sheets of cellulose-acetate and vinyl-acetal

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*We wish to acknowledge and express our appreciation of the utmost cooperation which the officers of the Experimental Office of the Bureau of Ordnance and the Naval Proving Ground have given us in making possible the experiments reported in this section.

resin of about 3/4-inch thickness, prepared by pressing together thinner materials in a heated hydraulic press. The results of these tests, conducted at a temperature of about 75° F., are shown in table IX. Lead bullets of .22 caliber, 1,200-feet-per-second velocity, were stopped in the blocks of plastic. (See fig. 11.) Lead bullets of .32 caliber, 800-feet-per-second velocity, and .38 caliber, 857-feet-per-second velocity, were deflected off the surface. Metal-jacketed bullets of .30 caliber, 1,397-feet-per-second velocity, passed through the plastics.

Tracer bullets of .30 and .50 caliber were fired from a machine gun at samples of cellulose-acetate, cellulose-nitrate, methacrylate resin, vinyl chloride-acetate resin, and laminated glass at ranges of 100 and 600 yards, the temperature being approximately 75° F. The breaks caused by the impact of these bullets afford useful information on the relative toughness of these materials. Some samples were merely penetrated by the bullets which left small holes with no radial cracks, while others were completely shattered by the larger-caliber bullets. These effects of tracer bullets on transparent plastics are clearly shown in figures 12 and 13. Figure 14 shows the type of break which is obtained when laminated glass made with cellulose-acetate and acrylate-resin plastics, respectively, are penetrated by tracer bullets.

VI. SUMMARY AND CONCLUSIONS

The Charpy impact strength of various transparent plastics was determined at 70° F. and 25° F. The cellulosic plastics and vinyl acetal resin have higher impact strengths than the methacrylate resins at 70° F., but they undergo a larger percentage decrease in impact strength at 25° F. than does the methacrylate resin. For example, at 70° F., the cellulose-acetate samples gave impact strength values of 1.9 to 3.6 foot-pounds per inch of thickness, whereas at 25° F. the strength varied from 0.25 to 1.5 foot-pounds per inch of thickness. The comparable figures for methyl-methacrylate resin are 0.40 to 0.46 foot-pounds per inch of thickness at 70° F., and 0.26 to 0.37 foot-pounds per inch of thickness at 25° F.

In drop tests with relatively hard and soft objects, such as a steel ball and a shot-filled tennis ball, respectively, it was observed that the plastics, in general, would withstand many more impacts from deformable bodies than from rigid bodies. A fair correlation exists between the Charpy impact strength value observed for a plastic and the height from which a steel ball must be dropped to break the plastic. A composite specimen of cellulose acetate, consisting of several sheets clamped together without cementing material, had greater resistance to the impact of the falling ball than did a laminated specimen made up of three layers of the usual aircraft grade of cellulose-acetate sheet bonded together with two interlayers of soft cellulose acetate commonly employed in laminating glass. A single sheet comparable in thickness to the composite and laminated specimens required approximately one-fourth and one-half as many impacts, respectively, to cause failure.

The resistance of transparent plastics to impact with a shot-filled sponge-rubber ball projected at high velocity from a gun, was determined. Plastic materials up to 0.5 inch in thickness, and glass products up to 1.2 inches in thickness, would not stop such a ball weighing 4 pounds and traveling at a speed of 400 feet per second. Four 1/8-inch-thick sheets of cellulose acetate bolted together in the test frame, and a sheet of tempered glass 1.2 inches thick were the only two samples which did not break when struck by a 3-pound rubber ball traveling at a speed of 300 feet per second with the windshield product inclined at an angle of 45° to the direction of the projectile, but specimens of both of these materials broke when fastened at an angle of 90° to the direction of the projectile.

National Bureau of Standards,

Washington, D. C., June 24, 1939.

TABLE I. Charpy and Dropped-Ball Impact Tests on Transparent Plastics[a)]

Material	Sample	Thickness mils	Charpy impact strength (notched)		Impact test with 0.5-lb. steel ball		
			Energy/thickness at 70° F. ft.-lb./in. of thickness	Energy/thickness at 25° F. ft.-lb./in. of thickness	Ball height ft.	Average number of balls required for failure	Number of specimens tested by falling-ball method
Cellulose acetate	A1	65	2.8	0.51	65	2.5	2
Do.	A2	96	3.2	.37			
Do.	A3	135	2.1	.25			
Do.	B2	94	1.9	.33	65	6	1
Do.	B4	98	3.0	1.51	65	2.5	2
Do.	B5	100	3.6	1.33	65	10	2
Do.	B6	67	2.7	.89	65	1	1
Do.	B7	95	2.4	1.16	65	6	2
Do.	B9	92	2.3	.29	65	5	1
Do.	C1	57	2.8	1.02	65	3	2
Do.	C3	125	2.4	.84	65	9	1
Do.	D1	165	2.3	.30			
Cellulose acetopropionate	AP1	55	1.4	1.5	65	6	1
Do.	AP3	58	1.9	.93	65	5	1
Do.	AP4	115	1.3	.62	65	17[b)]	1
Cellulose nitrate	E1	66	3.8	2.13	65	4	2
Do.	F1	63	4.4	2.60	65	5	2
Ethylcellulose	G1	59	3.1	2.49	---	---	-
Methyl methacrylate resin	K1	117	.46	.33	3	2	1
Do.	K4	88	.45	.26	---	---	-
Do.	K7	222	.44	.37	10	2	1
Do.	K8	218	.40	.36			
Vinyl chloride-acetate resin	L3	102	.4	.15	8	2	1
Vinyl acetal resin	N1	122	2.9	.65	65	11.5	2

a)The Charpy impact test specimens were 2.5 in. long, 0.5 in. wide, and thickness as received. The ball tests were made on specimens clamped in the frame (fig. 4) which has an opening 5.5 in. in diameter.

b)The last two impacts on this sample were made with a 1.2-lb. steel ball.

TABLE II. Effect of Holding Specimen in Edgewise Position on Charpy Impact Strength of Transparent Plastics

Material	Thick-ness mils	Charpy impact strength (notched)				Remarks
		Energy/thickness at 70° F. (no brackets) ft.-lb./in. of thickness	Energy/thickness at 70° F. (brackets) ft.-lb./in. of thickness	Energy/thickness at 25° F. (no brackets) ft.-lb./in. of thickness	Energy/thickness at 7° F. (brackets) ft.-lb./in. of thickness	
Cellulose aceto-propionate						
AP1	55	1.4	1.5	1.5	0.77	No plasticizer
AP2	107	1.4	1.4	1.2	.77	No plasticizer
AP3	58	1.9	1.4	.93	.62	15 percent triphenyl phosphate
AP4	115	1.3	1.7	.62	.63	15 percent triphenyl phosphate
Cellulose acetate						
A5	124	1.4	1.2	.60	.33	
Methyl methacrylate resin						
J3	123	.24	-	.31	-	
Propyl methacrylate resin						
J5	136	.22	.27	.29	.27	
Butyl methacrylate resin						
J6	139	.23	.29	.29	.27	
Styrene resin						
HS1	514	.59	-	.55[a)]	-	Low viscosity resin
HS2	507	.47	-	.45[a)]	-	High viscosity resin

[a)] Temperature of test was 7° F.

TABLE III. Dropped Ball Impact Tests on Plastics
with Various Types of Inelastic Bodies

Material	Thickness mils	Type of ball	Number of impacts from 65 feet to cause failure
Cellulose acetate			
A1	65	1-lb. shot-filled tennis ball	7
C1	57	1-lb. shot-filled tennis ball	8
B7	95	1-lb. shot-filled tennis ball	19
C6	138	1.4-lb. shot-filled tennis ball	9
C6	138	4-lb. filled sponge-rubber ball	7[a]
Cellulose nitrate			
E1	66	1.4-lb. shot-filled tennis ball	8

[a] This specimen was tested in the frame (fig. 10), which has an opening 11 inches square. The other materials listed in this table were tested in the frame (fig. 4), which has an opening 5.5 inches in diameter.

TABLE IV. Ball Impact Tests of Single, Laminated, and Composite Cellulose-Acetate Specimens

(All tests made with a 1.2-lb. steel ball dropped from a height of 65 feet onto specimens clamped in the frame (fig. 4) which has an opening 5.5 in. in diameter)

Material	Type of specimen	Total thickness mils	Number of impacts required for failure
B3	Single (original sheet)	65	2
C2	Single (original sheet)	95	3
A2	Single (original sheet)	96	4
B14	Single (original sheet)	107	1
B14	Single (original sheet)	107	1
C3	Single (original sheet)	125	3
B13	Single (original sheet)	125	2
B13	Single (original sheet)	125	2
B13	Single (original sheet)	125	2
C6	Single (original sheet)	138	2
C6	Single (original sheet)	138	4
C6	Single (original sheet)	138	4
B7	Single (pressed from 3 pieces of 95 mil stock)	242	2
B7	Single (pressed from 3 pieces of 95 mil stock)	242	5
C2	Single (pressed from 3 pieces of 95 and 1 piece of 60 mil stock)	292	5
B7	Laminated (2 layers of soft acetate between 3 layers of B7)	238	5
B7	Laminated (2 layers of soft acetate between 3 layers of B7)	238	5
B7	Laminated (2 layers of soft acetate between 3 layers of B7)	238	7
C1	Composite (3 pieces of 55 mil stock)	165	5
C2	Composite (2 pieces of 95 mil stock)	191	9
B3	Composite (4 pieces of 65 mil stock)	256	13
C2	Composite (3 pieces of 95 mil stock)	285	12
C3	Composite (3 pieces of 125 mil stock)	366	13

TABLE V. Falling-Dart Impact Tests on Plastics

(Specimens were tested in the frame shown in fig. 3, which has an opening 11-3/8 in. square, except the last two materials, A5 and C7, which were clamped in the frame shown in fig. 7, having an opening 11 in. square)

Temperature	Material	Thickness in.	Failure Height ft.	Failure Number of impacts at that height	Total number of impacts	Heights in feet and number of impacts at each height	Remarks
100° F.	K18	0.268	30	1	3	20(1); 25(1); 30(1)	13 pieces
100° F.	K23	.254	30	1	2	25(1); 30(1)	17 pieces
100° F.	K23	.268	30	1	1	30(1)	15 pieces
0° F.	K18	.261	25	1	2	20(1); 25(1)	26 pieces
0° F.	K18	.253	30	1	2	25(1); 30(1)	40 pieces
100° F.	K38	.395	25	1	2	20(1); 25(1)	10 pieces
100° F.	K38	.376	---	-	2	25(1); 30(1)	Sample cracked when hit by metal on rebound
100° F.	K38	.385	35	1	1	35(1)	17 pieces
100° F.	K38	.380	35	1	1	35(1)	11 pieces
0° F.	K38	.388	40	1	6	20(1); 30(1); 35(3); 40(1)	26 pieces
0° F.	K38	.396	40	1	3	25(1); 35(1); 40(1)	16 pieces
100° F.	K39	.532	35	1	4	20(1); 25(1); 30(1); 35(1)	11 pieces
100° F.	K39	.547	50	1	3	35(2); 50(1)	14 pieces
100° F.	K39	.526	---	-	1	40(1)	Sample cracked when hit by metal on rebound
0° F.	K39	.559	50	1	2	35(1); 50(1)	18 pieces
0° F.	K39	.558	50	1	1	50(1)	14 pieces
0° F.	K39	.520	---	-	2	40(1); 45(1)	No failure
100° F.	K40	.763	---	-	1	50(1)	No failure
0° F.	K40	.734	---	-	1	50(1)	No failure
100° F.	C3	.125	---	-	1	20(1)	Pulled through frame
0° F.	C3	.125	25	1	2	20(1); 25(1)	70 pieces
0° F.	A3	.135	25	1	1	25(1)	> 100 pieces
0° F.	A3	.135	20	1	1	20(1)	> 100 pieces
100° F.	A5	.124	---	-	1	35(1)	No failure
100° F.	C7	.127	---	-	1	35(1)	No failure

TABLE VI. Impact Tests Made with 2-Inch Air Gun[a)]

Material	Thickness	Projectile				Number of shots required for failure
	mils	Type	Weight lb.	Approximate muzzle velocity ft./sec.	Impact energy ft.-lb.	
Cellulose nitrate						
E1	66	Rubber wrapped in cellophane	0.555	144	179	4
E1 (composite, 3 sheets of 66 mil stock)	198	Hardwood	.5	150	175	1
F1	63	Rubber in cellophane	.555	144	179	4
Cellulose acetate						
B3	65	Rubber in cellophane	.555	144	179	8
B3	65	Rubber in cellophane	.555	144	179	12 plus 3 of the soft rubber projectiles
B3	65	Soft rubber in cardboard	.48	169	213	3
B3	65	Soft rubber in cardboard	.48	169	213	4
B3	65	Soft rubber in cardboard	.48	169	213	5
C3	125	Soft rubber in cardboard	.48	169	213	11 shots without failure
Laminated glass (12-14 oz. sheet glass, cellulose-acetate plastic)	150	Soft rubber in cardboard	.48	169	213	1
Plate glass	250	Soft rubber in cardboard	.48	169	213	1
Tempered glass	250	Soft rubber in cardboard	.48	169	213	6 shots without failure
Laminated glass (plate glass; vinyl acetal plastic)	250	Soft rubber in cardboard	.48	169	213	1

a)The plastics were clamped in the frame (fig. 4), which has an opening 5.5 in. in diameter; the laminated plastics were tested in the frame (fig. 3), which has an opening 11-3/8 in. square.

TABLE VII. High Velocity Impact Tests on Cellulose-Acetate Plastic

	Description of material	Total thickness in.	Size of opening of test frame in.	Angle of impact	Weight of projectile lb.	Velocity of projectile ft./sec.	Impact energy ft.-lb.	Result	Remarks
1	Cellulose acetate (1 sheet)	0.094	13 X 17	90°	4	293	5,340	Penetrated	Hit at center
2	Cellulose acetate (4 sheets)	.516	13 X 17	90°	4	403	10,100	Penetrated	Hit at center, sheared at edges
3	Cellulose acetate (4 sheets)	.516	13 X 17	90°	3	308	4,420	Penetrated	Hit near corner
4A	Cellulose acetate (4 sheets)	.516	13 X 17	48°	3	298	4,140	Stopped	Hit at center
4B	Same sample as above	.516	13 X 17	45°	4	350	7,620	Penetrated	Hit near corner
5	Cellulose acetate (1 sheet)	.51	13 X 17	45°	3	280	3,660	Penetrated	Hit near corner
6	Cellulose acetate (4 sheets)	.516	13 X 17	45°	4	303	5,710	Penetrated	Hit near center

TABLE VIII. High Velocity Impact Tests on Glass Windshield Products

	Description of material	Total thickness in.	Size of opening of test frame in.	Angle of impact	Weight of projectile lb.	Velocity of projectile ft./sec.	Impact energy ft.-lb.	Result	Remarks
1	Laminated glass 1-ply 1/4-inch tempered polished plate; plastic 1/40-inch special resin 1-ply 3/32-inch sheet	0.36	13 X 17	90°	3	288	3,870	Penetrated	Hit near center (sheet side toward gun)
2	Tempered glass (1 piece)	1.25	11 X 11	90°	3	288	3,870	Penetrated	Hit near one side
3	Laminated glass 7-ply 5/64-inch polished plate; 6-ply 1/40-inch vinyl plastic	.7	11 X 11	90°	3	296	4,090	Penetrated	Hit near center
4	Laminated glass 2-ply 7/64-inch polished plate; 1-ply 1/10-inch vinyl plastic	.32	11 X 11	90°	3	248	2,870	Penetrated	Hit near frame
5	Same material as No. 1	.36	13 X 17	45°	3	276	3,550	Penetrated	Hit near center
6A	Same material as No. 2.	1.25	11 X 11	45°	3	341	5,420	Stopped	Hit near center
6B	Same sample as above	1.25	11 X 11	45°	4	279	4,840	Penetrated	Hit near frame

TABLE IX. Pistol Bullet Impact Tests on 3/4-Inch-Thick Specimens

Specimen	Type of bullet (caliber, etc.)	Muzzle velocity ft./sec.	Muzzle energy ft.-lb.	Results
Cellulose acetate				
A3	22 long, lead	1,250	121	Stopped in plastic
A3	32 S & W long, lead	810	143	Bounced off
A3	30 Mauser metal-jacketed	1,397	373	Penetrated
B2	32 S & W long, lead	810	143	Bounced off
B2	22 long, lead	1,250	121	Stopped in plastic
B8	32 S & W long, lead	810	143	Bounced off
B8	38 S & W Special, lead	857	258	First 38-caliber bullet bounced off
				Second bullet, struck 1 inch from first, split the sample but was deflected
				Third struck 1/2 inch from edge, cracked plastic, but bounced off
Vinyl resin				
N1	22 long, lead	1,250	121	Stopped in plastic
	30 Mauser metal-jacketed	1,397	373	Penetrated
Glycerylphthalate*				
T1	22 long, lead	1,250	121	Shattered

*0.29 inch in thickness.

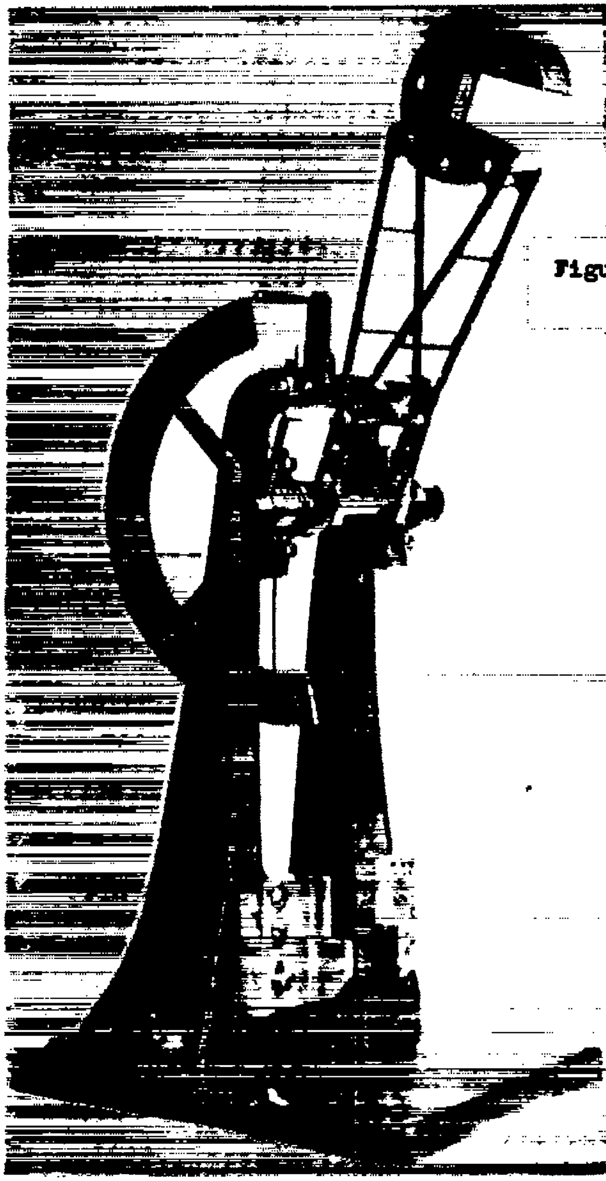


Figure 1.- Apparatus for determining Charpy impact strength.

Figure 3.- Wooden frame used to hold 12"×12" specimens in the falling-dart impact test.

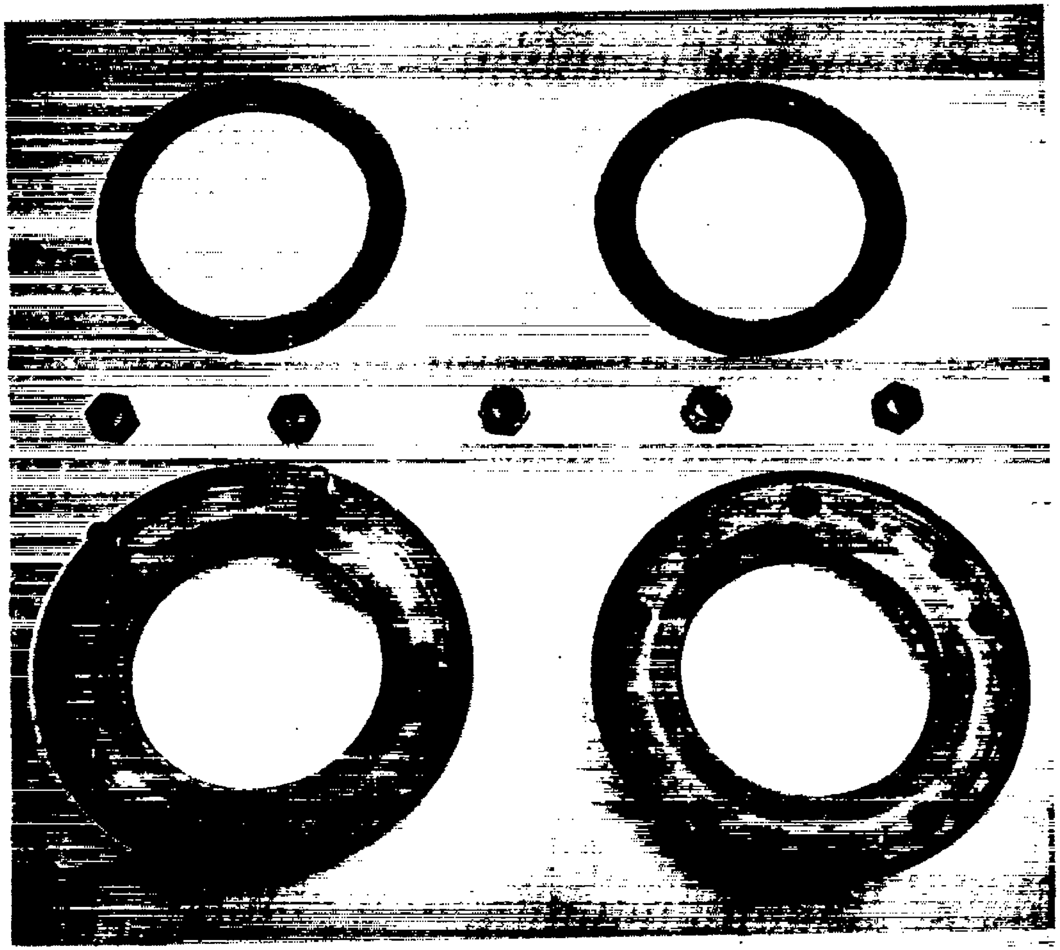


Figure 4.- Circular frame used to hold plastics in the falling-ball impact test.

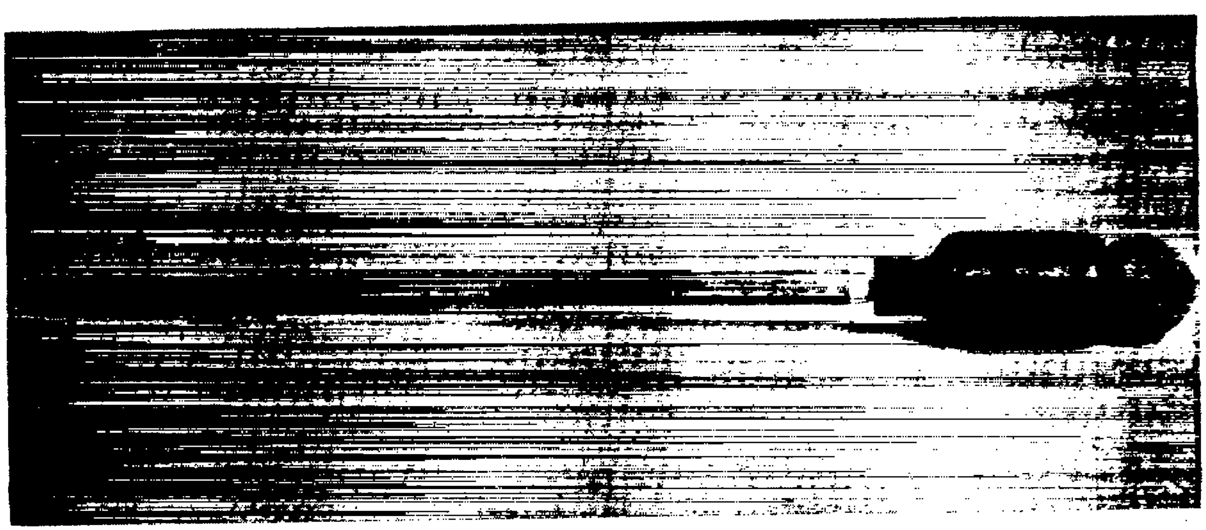
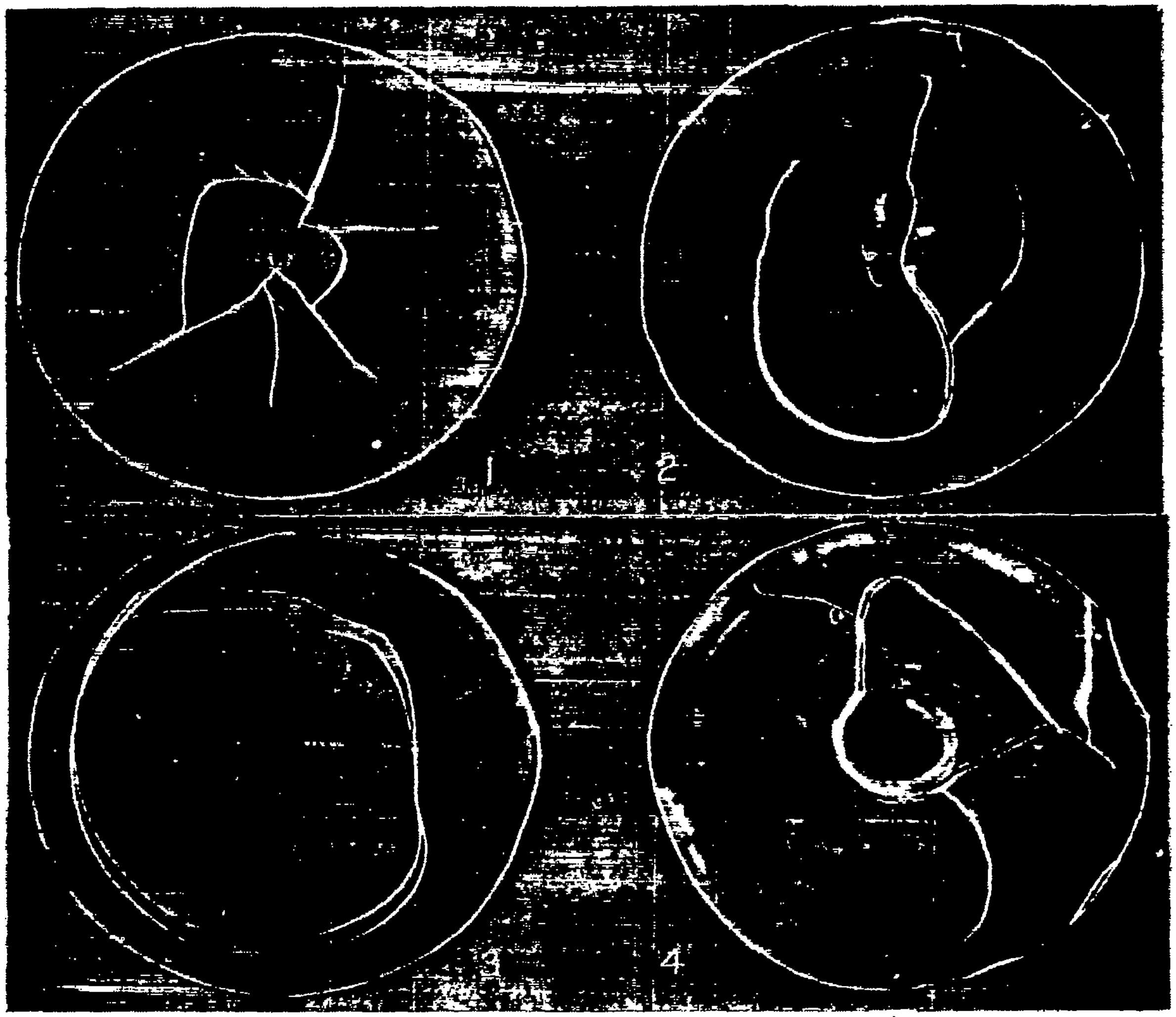


Figure 6.- Dart used in impact tests on plastics and glass windshield products.



1. Cellulose acetate B4; failed on second impact of 0.5 lb. steel ball dropped 65 feet.
2.- Cellulose acetate B5; failed on eighth impact of 0.5 lb. steel ball dropped 65 feet.
3.- Cellulose acetate A1; failed on seventh impact of 1 lb. shot-filled tennis ball dropped 65 feet.
4.- Cellulose nitrate E1; top sheet of composite specimen consisting of 3 sheets of 66 mil stock; failed on first impact of 0.5 lb. hardwood projectile fired from air gun at velocity of 150 ft. per sec.

Figure 5.- Plastic specimens after impact tests.

Figure 7.- Frame used to hold 12" × 12" specimens for high-velocity impact tests.

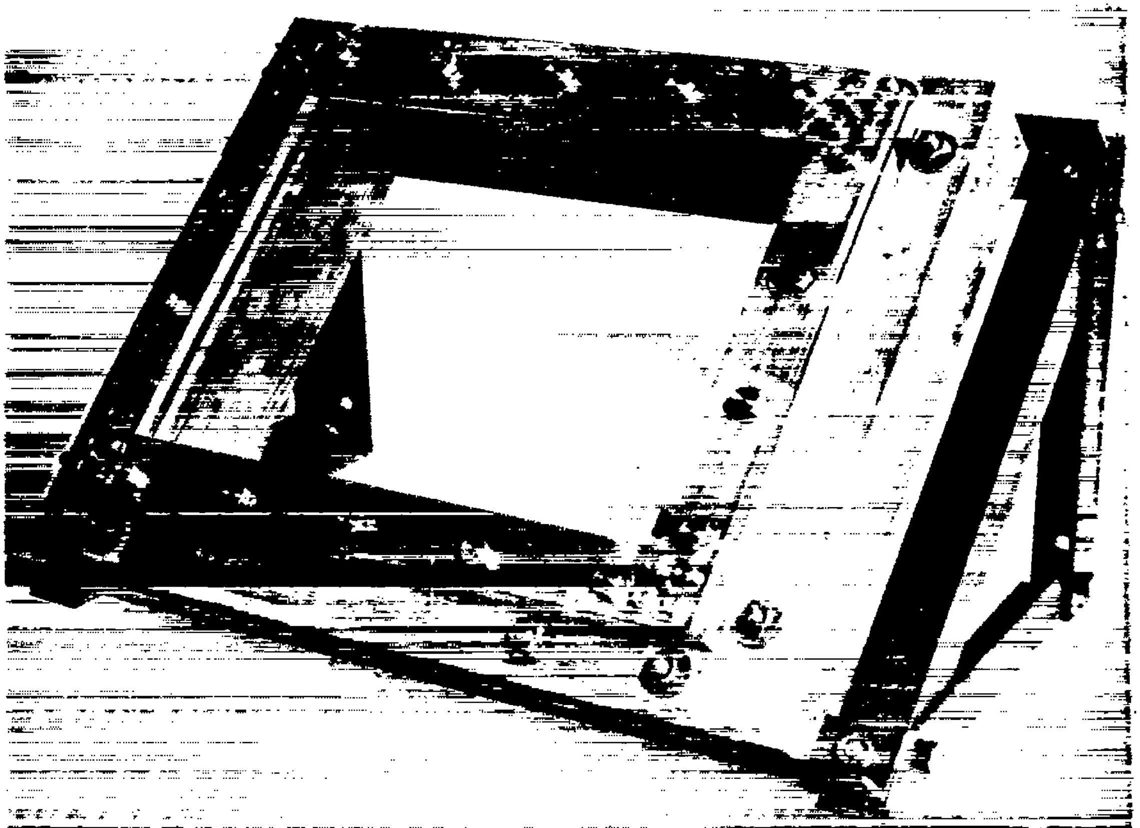


Figure 10.- Frame used to hold 14" × 18" specimens for high-velocity impact tests.

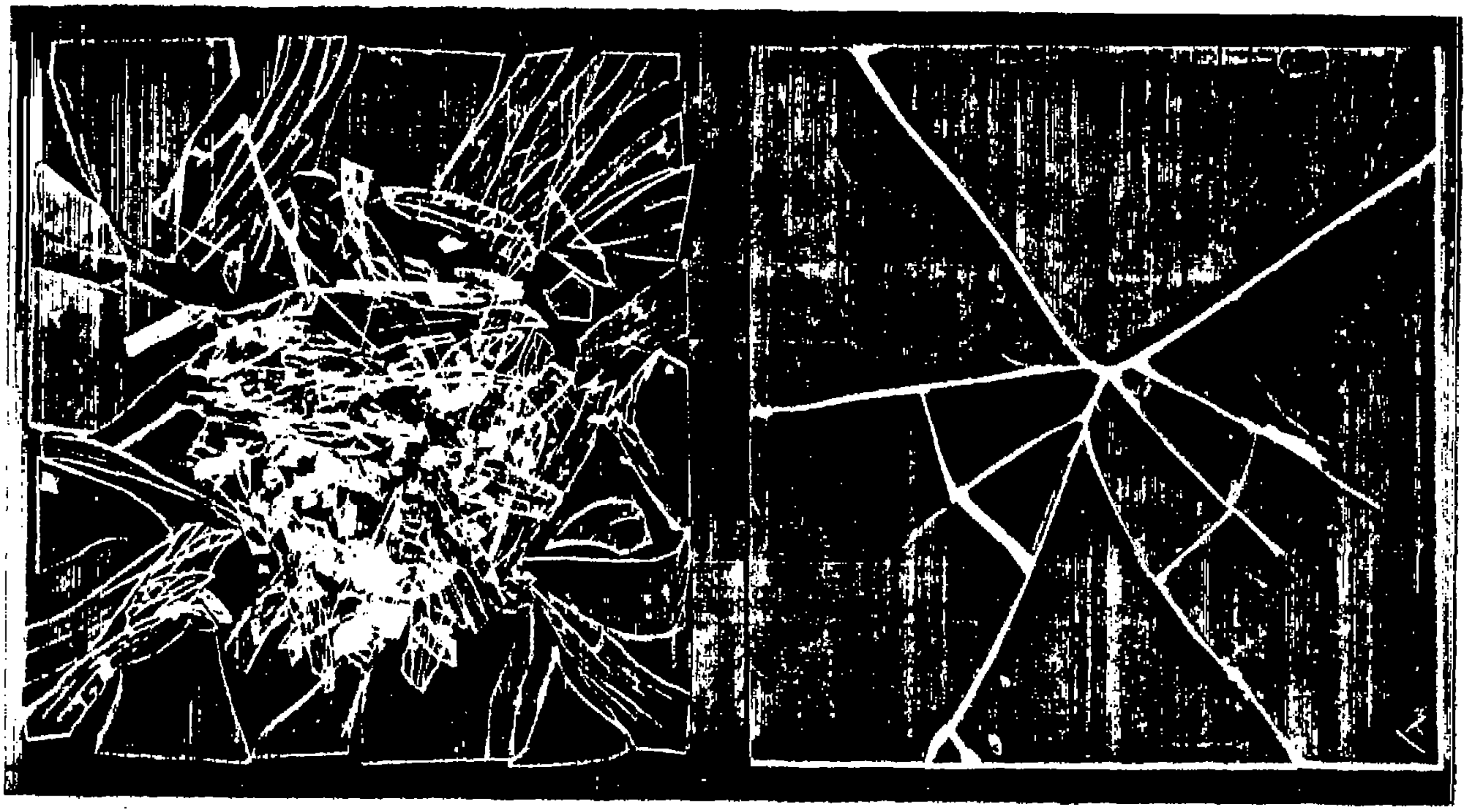


Figure 8.- Plastic specimens after impact tests at
0° F with falling dart.
Left: Cellulose acetate A3.
Right: Methyl methacrylate resin K38.

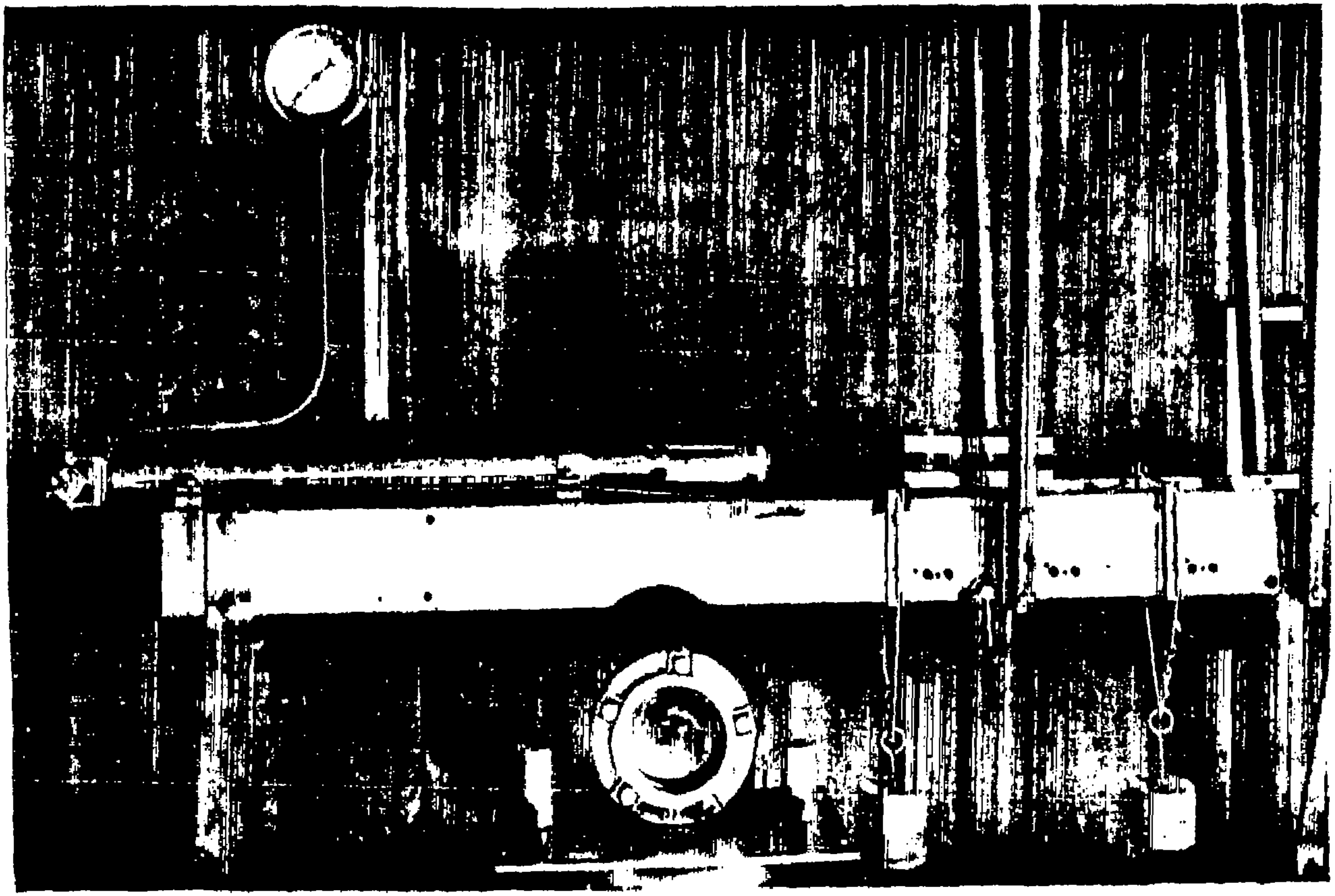


Figure 9.- Air gun used for high-velocity impact tests on plastics and glass windshield products.

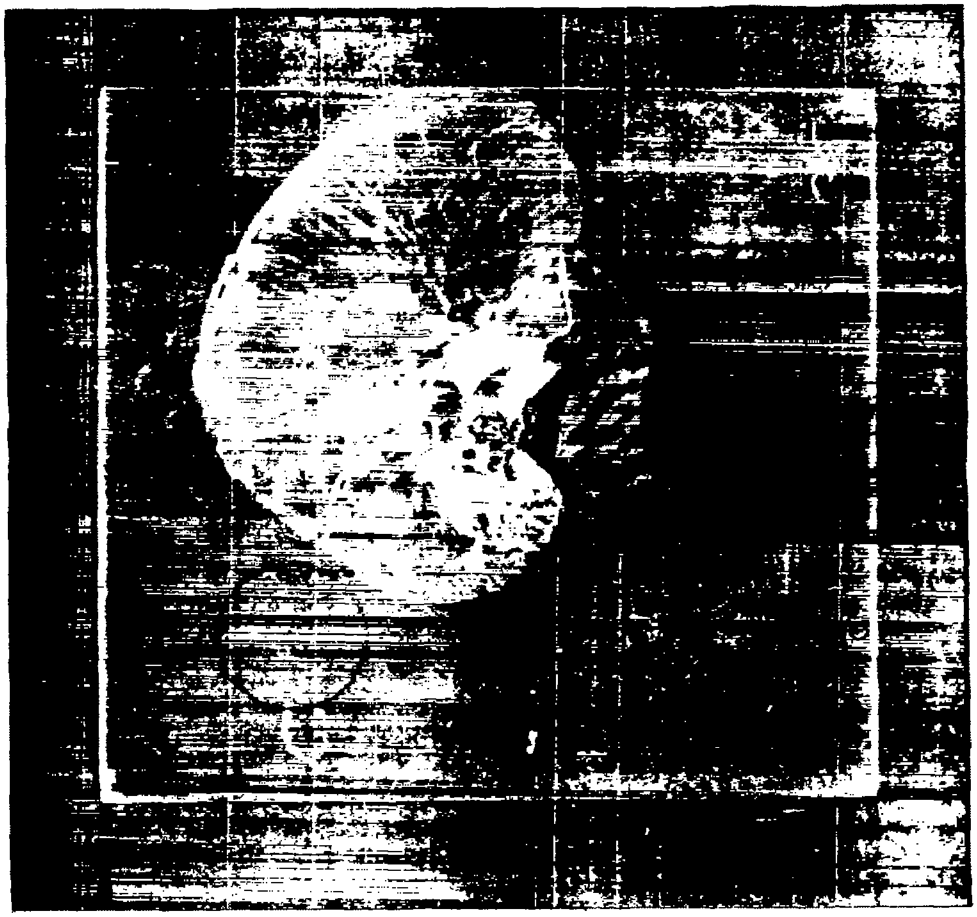
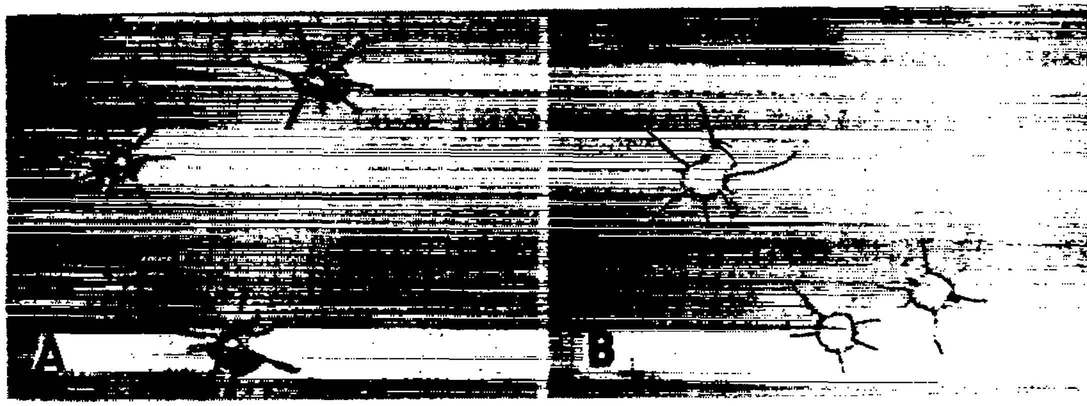
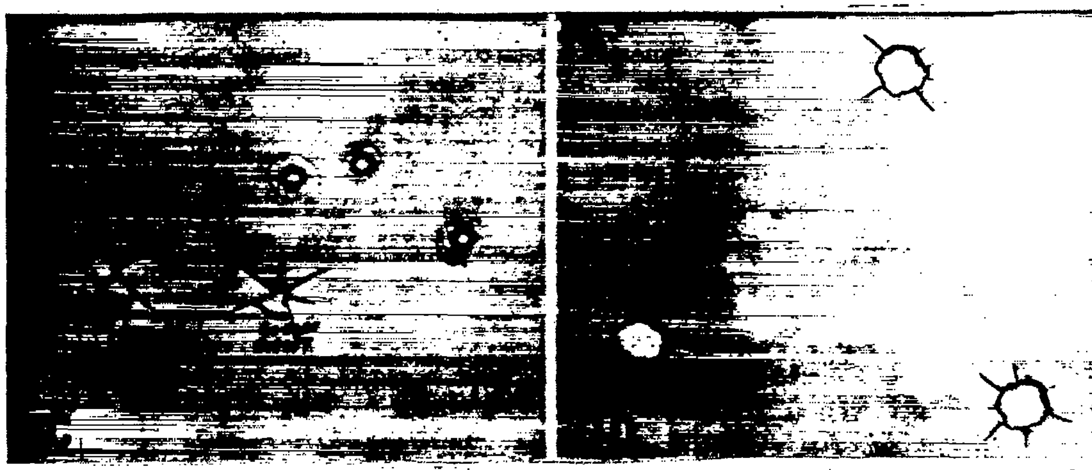


Figure 11.- Cellulose acetate B2 with .22 caliber, long, lead-nosed bullet buried in it. A .32 caliber, S and W long, lead-nosed bullet was deflected from the surface within the area surrounded by the circle.



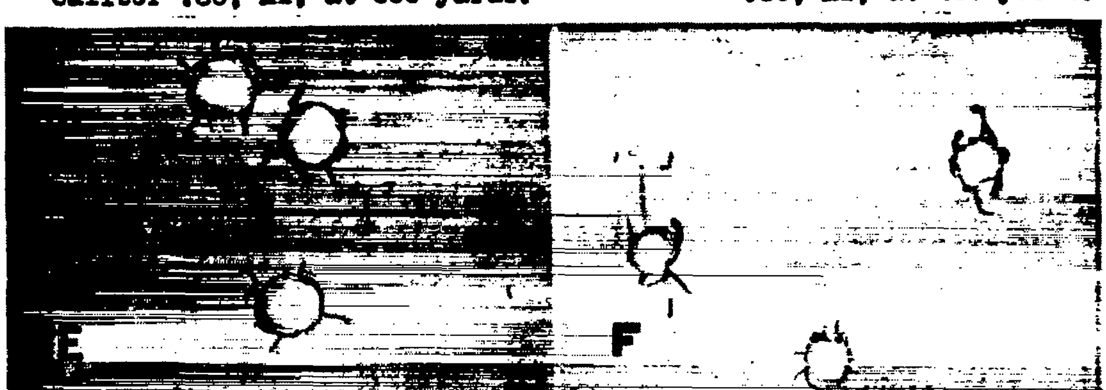
A. Acrylate resin, K1, 0.113 in. thick; three tracer bullets caliber .30, M1, at 100 yards.

B. Acrylate resin, K9, 0.067 in. thick; three tracer bullets caliber .50, M1, at 100 yards.



C. Cellulose nitrate, F1, 0.062 in. thick; three tracer bullets caliber .30, M1, at 100 yards; two tracer bullets caliber .30, M1, at 600 yards.

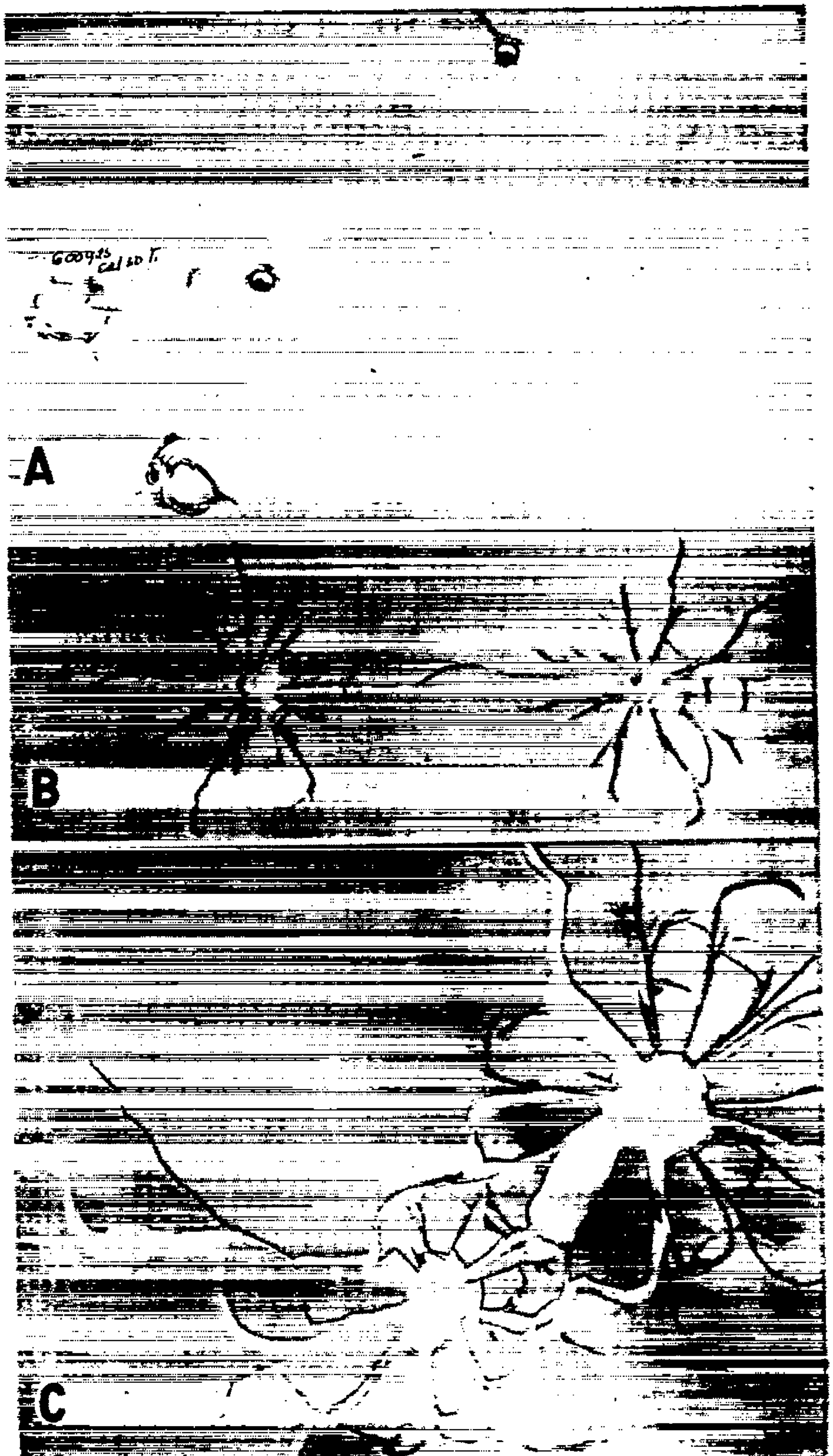
D. Cellulose nitrate, E1, 0.066 in. thick; three tracer bullets caliber .50, M1, at 100 yards.



E. Cellulose acetate, C2, 0.095 in. thick; three tracer bullets caliber .50, M1, at 100 yards.

F. Cellulose acetate, B3, 0.066 in. thick; three tracer bullets caliber .50, M1, at 100 yards.

Figure 12.- Effect of tracer bullets on transparent plastics.

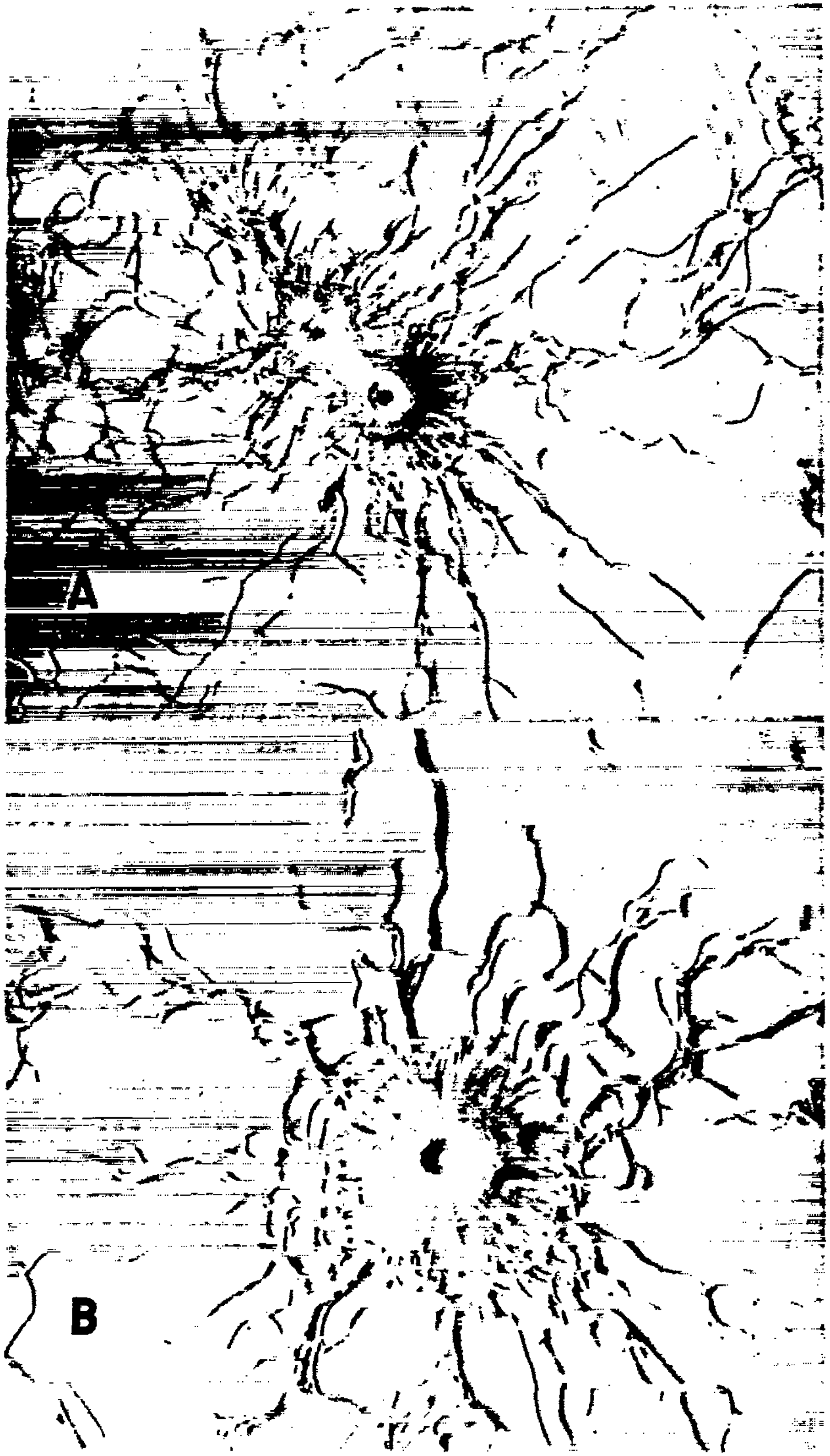


A. Cellulose acetate, A2, 0.095 in. thick; three tracer bullets caliber .30, M1, at 100 yards; one tracer bullet caliber .30, M1, at 600 yards.

B. Vinyl chloride-acetate resin, L3, 0.100 in. thick; two tracer bullets caliber .30, M1, at 100 yards.

C. Vinyl chloride-acetate resin, L3, 0.100 in. thick; two tracer bullets caliber .50, M1, at 100 yards.

Figure 13.- Effect of tracer bullets on transparent plastics.



A. Plate glass bonded with cellulose acetate plastic, X5, 0.188 in. thick; two tracer bullets caliber .30, M1, at 100 yards.

B. Plate and sheet glass bonded with acrylate resin plastic, Y5, 0.238 in. thick; one tracer bullet caliber .50, M1, at 100 yards.

Figure 14.- Effect of tracer bullets on laminated glass.